AFRL-AFOSR-JP-TR-2022-0075

Quantum Accelerator: Towards sub-picotesla quantum diamond magnetometers for Defense

DAVID SIMPSON
UNIVERSITY OF MELBOURNE
GRATTAN ST
PARKVILLE, VIC, 3010
AUS

08/29/2022
Final Technical Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
Air Force Office of Scientific Research
Asian Office of Aerospace Research and Development
Unit 45002, APO AP 96338-5002

REPORT DOCUMENTATION PAGE

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE 20220829	**2. REPORT TYPE** Final	**3. DATES COVERED**	
		START DATE 20201115	**END DATE** 20220514

4. TITLE AND SUBTITLE
Quantum Accelerator: Towards sub-picotesla quantum diamond magnetometers for Defense

5a. CONTRACT NUMBER	**5b. GRANT NUMBER** FA9550-21-1-0036	**5c. PROGRAM ELEMENT NUMBER**
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
David Simpson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) UNIVERSITY OF MELBOURNE GRATTAN ST PARKVILLE, VIC 3010 AUS	**8. PERFORMING ORGANIZATION REPORT NUMBER**

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AOARD UNIT 45002 APO AP 96338-5002	**10. SPONSOR/MONITOR'S ACRONYM(S)** AFRL/AFOSR IOA	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)** AFRL-AFOSR-JP-TR-2022-0075

12. DISTRIBUTION/AVAILABILITY STATEMENT
A Distribution Unlimited: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The primary objective of this work was to engineer NV ensembles at varying concentrations levels in (111) diamond. Diamond growth on (111) surfaces offers the potential to engineer NV centres in diamond that are aligned in a single orientation. The alignment improves the measured NV spin contrast and can lead to an enhanced magnetic sensitivity. Diamond material has been optimized for nanoscale magnetic sensing and imaging applications. In this work, we focused on achieving thick (111) NV ensembles suitable for bulk precision magnetometry applications.

Using the commercial-grade diamond CVD reactor at the University of Melbourne, the team has engineered the first ultrapure (111) diamond layers in Australia. This represents the starting point for the NV incorporation study. We have characterized the surface morphology, optical properties and the growth rates from a series of nine diamond samples. The team has also refined the surface treatment prior to CVD growth to reduce substrate imperfections seeding into the grown layers.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT** SAR	**18. NUMBER OF PAGES** 7
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U		

19a. NAME OF RESPONSIBLE PERSON MICHAEL RICHARDS	**19b. PHONE NUMBER** *(Include area code)* 3152277000

AFOSR
Final Report

Award Number: FA9550-21-1-0036

Project Title: Towards sub-picotesla quantum diamond magnetometers for defense

Start Date: 10th of November 2020

Principal Investigator:

Dr David Simpson
School of Physics, University of Melbourne, Victoria, Australia
Email: simd@unimelb.edu.au

Co-Investigators:

Dr Alastair Stacey
School of Science, RMIT University, Victoria, Australia
Email: alastair.stacey@rmit.edu.au

Prof Brant Gibson
School of Science, RMIT University, Victoria, Australia
Email: brant.gibson@rmit.edu.au

Prof Andrew Greentree
School of Science, RMIT University, Victoria, Australia
Email: andrew.greentree@rmit.edu.au

Prof Lloyd Hollenberg
School of Physics, University of Melbourne, Victoria, Australia
Email: lloydch@unimelb.edu.au

Dr Liam Hall
School of Physics, University of Melbourne, Victoria, Australia
Email: liam.hall@unimelb.edu.au

Dr Scott Foster
Defence Science and Technology Group, Edinburgh, South Australia
Email: scott.foster@defence.gov.au

Section 2: Technical Report

Accomplishments:

The current project aims to systematically study the production of NV ensembles in (111) diamond. The study is being undertaken at the cutting-edge *National Facility for Quantum Diamond* at the *University of Melbourne.* The study aims to determine the optimal CVD growth parameters to achieve dense preferential alignment of NV defects in diamond over tens of microns for ultra-sensitive precision magnetometry. The team will characterise the magnetic field sensitivity of these novel materials using our world class quantum sensing laboratories and provide a direct comparison with (100) CVD diamonds grown in the same facility. This project will deliver critical new insights into the sensitivity limits of diamond-based magnetometers, and generate material that will drive a range of diamond quantum-sensing solutions for related problems in Defense, medicine, healthcare and mining.

The specific Research Objectives (ROs) of the proposal are listed below:

- RO1 - Explore the ideal growth conditions for aligned NV centres in isotopically pure ^{12}C (111) diamond.
- RO2 - Generate a unique set of samples with [N] concentrations varying from 0.1 ppm to 20 ppm.
- RO3 - Characterise the magnetic sensitivity and noise floor of the grown material and provide a direct comparison to standard 1.1% ^{13}C (100) diamond samples.

Reporting period 10/11/20 – 11/8/22:

The team has experienced significant COVID-19 related research delays throughout 2021 which has impacted the research program. This was discussed in the no-cost extension which was granted on the 9th of November. Despite the research delays, the team has been able to make major advances to the program which are discussed below.

Major Activities:

1) *Establishment of cutting-edge magnetic sensitivity characterization platform*
   In the no cost extension phase of the program the team has focused our efforts on designing and constructing a unique test and measurement platform to evaluate the magnetic sensitivity of diamond materials. The T&E platform utilizes the 3D Helmholtz coil that was acquired under this proposal. The 3D Helmholtz system is critical for delivering control magnetic test signals and can also be used to actively cancel magnetic noise from the laboratory environment. This capability provides allows the magnetic sensitivity to be measured as a function of bandwidth and will allow us to probe the fundamental noise sources of our diamond magnetometer. This is the first T&E measurement facility of its kind in Australia and will be open to groups building different types of magnetic sensors to provide a fair and even comparison against cutting edge technology.

2) *Optimizing the growth of (111) diamond*
   Despite the extremely limited access to the diamond growth facilities throughout 2021, the team has conducted a series of diamond growths on nine (111) diamond substrates. The focus of the preliminary study was to identify the parameters which impact the diamond growth rate and surface morphology. The outcome from the initial series of growths suggests that low chamber pressure and low plasma temperatures appear optimal for smooth (111) diamond growth over

several microns. The major outcome from this initial work is the production of Australia's first ultrapure (111) diamond layers. In the no cost extension phase, we took delivery of the new diamond chemical vapour deposition (CVD) reactor. The reactor is currently being commissioned and will be up and running by the end of year. The quantum grade reactor will be used to growth new isotopically engineered 12C diamond material which can now be benchmarked and evaluated using the T&E platform.

3) *Characterisation of (111) diamond materials*
The second major outcome achieved during the reporting period was the development of a confocal microscope to study the optical and spin properties of the NV centres incorporated into the (111) diamond crystal. Alister Chew, a PhD student assigned to the project has established the optical characterization facility to image the NV centres grown into the diamond materials and has benchmarked the system using intrinsic NV centres found in the (111) diamond substrates. This facility will be used to characterise the magnetic sensitivity of the (111) grown material and to verify whether oriented NV growth can be achieved under the optimal growth parameters identified in RO1. This research will be ongoing as Alister continues his PhD. Our team will acknowledge the important contribution the AFOSR grant has made to the T&E platform and future isotopically diamond growth in publications arising from this work.

4) *Purchasing of critical infrastructure*
There were no additional purchases in the no-cost extension period. We have purchased the required infrastructure to grow isotopically pure ^{12}C (111) diamond material. The ^{12}C methane gas required for the isotopically pure growth has arrived and will be fitted to the new diamond CVD reactor by the end of 2022. We have experienced considerable delay with the new quantum-grade diamond CVD reactor which prevented progress towards ROs 2 and 3. We pivoted and tried to use the commercial-grade CVD reactor which has demonstrated sufficient purity levels to carry out the research program. However, it was clear that the substrate temperature plays a critical role on the growth of <111> diamond. The quantum-grade reactor has much finer control and measurement of the substrate temperature, which will result in most consistent diamond growths into the future. As discussed above, we have also purchased a 3D Helmholtz coil and current controller to undertake the magnetic sensitivity characterization and this system is now fully functioning in the laboratory.

5) *Training of higher degree students*
The last major achievement of the short research program in was the training and development of future quantum engineers. Alister Chew has spent the majority of 2021 and 2022 understanding the nuances of diamond growth and the optical characterization of defect centres in diamond. Alister has worked with the team of diamond growth experts and also trained additional graduate research students in diamond fabrication. Dr Chris Lew has also been appointed to develop precision diamond magnetometers. Chris has led the establishment of the T&E platform with input from the team and will guide the future measurement and characterization program of work. Additional post-doctoral researchers have been recruited to the project included Dr Fernando Menseses formally from the City College of New York. Dr Menseses is exploring artificial intelligence (AI) and machine-learning (ML) approaches which will enhance the performance of diamond magnetometers for magnetic anomaly detection. This talent pipeline of researchers will be critical for translating this cutting-edge technology.

Future plans and possible funded projects.
The quantum U tech accelerator program has been a wonderful initiative to be part of and has helped our team strengthen and develop new US collaborations in quantum sensing. We have had very productive conversations with Dr Robert Bedford, Dr Luke Bissell and Dr Michael Slocum from the Air Force Research Laboratory at Wright-Patterson Air Force Base, Ohio and collectively we have submitted an expression of interest to work together through the International Cooperative Research and Development (ICR&D) program on novel diamond photonic architectures using <111> diamond material. Our team has significant expertise in diamond fabrication and diamond photonics and given the new investments in nanoscale fabrication facilities at the University of Melbourne and RMIT University, we are well positioned to explore new diamond waveguide geometries that will enhance precision magnetometers and biological quantum sensing platforms. The growth of <111> diamond membranes will be critical for coupling the photon emission from NV defects into diamond waveguide modes. NV centres aligned along the <111> crystallographic plane couple preferentially to diamond photonic waveguides and provide enhancement in the collection efficiency up to a factor of 10. Therefore, the learnings from this project will drive new directions in diamond photonics and quantum sensing applications. We seek to present this project for funding in an upcoming white paper.

Impacts:

The preliminary findings from the initial diamond growths are promising and represent the first ultrapure (111) single crystal diamond growths in Australia. The team is excited about the prospects of furthering this research through the new quantum grade diamond CVD reactor and will seek to disseminate the results to the scientific and broader community as the opportunity arises.

The team has taken the opportunity to showcase this research program to the defense community in Australia, at the Army Quantum Technology Challenge 2021 event, where our team was selected to prototype and showcase a fibre-based diamond magnetometer. Following our demonstration and presentation, our team was one of two teams nationally selected to progress to Stage 2 funding. Our project was also highlighted in a major presentation delivered by CI Gibson to the US Office for Navel Research Global X program. The Global X program meeting had representatives from the US Department of Defense, Australian Defence Force and a host of potential Defense industry partners. This material science program of research is critical to many of the Defense projects our team members currently lead. The outcome from the next six months will help shape the future direction of diamond-based magnetometry research.

Aspects of this research have been submitted to the Australian Institute of Physics Congress in the Precision Quantum Sensing focus group. This will provide an opportunity to showcase the T&E platform we have developed and present our latest research on diamond vector magnetometry.

Research outcomes:

1. C. T.-K. Lew, A. Chew, F. Meneses, A. Sivamalai, L. Anderson, A. Seyers, L. T. Hall, A. Silvester, A. D. Greentree, B. C. Gibson, L. C. L. Hollenberg, and D. A. Simpson, "*Vector Magnetometry Using Nitrogen-vacancy Centers in Diamond*" AIP Congress (submitted) 2022.

2. A. S. C. Chew, A. Stacey, C. T. -K. Lew, S. A. Vahid, H. Ebendorff-Heidepriem, S. Foster, A. D. Greentree, B. C. Gibson, D. A. Simpson, "*Isotopic enrichment of diamond for bulk nitrogen-vacancy*

magnetometry applications" AIP Congress (submitted) 2022.

3. C. T. -K. Lew, A. Chew, L. Anderson, F. Meneses, L. T. Hall, A. Sivamalai, L. C. L. Hollenberg, A. D. Greentree, B. C. Gibson, A. Silvester, A. Sayers, and D. A. Simpson, "*Quantum Diamond Magnetometers for Precision Vector Magnetic Field Sensing*", AIP Congress (submitted) 2022.

Changes:

Changes in approach
Our approach to the ROs listed above remained the same as proposed until the no cost extension period when a greater emphasis was put towards establishing the T&E platform given the delay encountered with the delivery of the new diamond CVD reactor and the sub-optimal performance of the existing commercial-grade diamond CVD reactor. Our preliminary studies indicate that the purity levels of the <111> are sufficient to undertake the material study however the current temperature stability limited detailed comparisons between samples. This will be rectified with the commissioning of the new CVD system.

Problems or delays
There have been significant research delays as a result of the COVID-19 pandemic. Melbourne experienced one of the longest lockdowns in the world, 262 days in total. The lockdowns severely limited access to the experimental facilities at both the University of Melbourne and RMIT, resulting in a significant loss in productivity in a heavily experimental program. The limited access to the laboratories resulted in a limited number of diamond growths over the reporting period. In addition to the laboratory access issues, we suffered significant delays with the production and delivery of the new quantum grade diamond CVD reactor. Shipping delays also occurred with the 3D Helmholtz coils and ^{12}C methane gas. Despite these significant challenges the team was able to navigate through this to deliver meaningful scientific outcomes that will guide future research projects.

Expenditure Impacts
The majority of the funds have been expended and the remaining funds will be used to develop the additional computational resources required to run the 3D Helmholtz coil. A minor change to the budget was approved by Program Manager Dr Christopher Vergien on the 19th of March 2021. The cost of the 3D Helmholtz system increased above the budget estimate and we therefore reduced the allocation of funds for the ^{12}C methane gas. The shortfall was supplemented by additional funds secured by PI Simpson.

Technical Updates:

Team members: PI: David Simpson (University of Melbourne), **CIs:** Alastair Stacey (RMIT), Brant Gibson (RMIT), Andrew Greentree (RMIT), Lloyd Hollenberg (University of Melbourne), Liam Hall (University of Melbourne), Scott Foster (Defence Science and Technology Group)

The primary objective of this work is to engineer NV ensembles at varying concentrations levels in (111) diamond. Diamond growth on (111) surfaces offers the potential to engineer NV centres in diamond that are aligned in a single orientation (see Figure 1). The alignment improves the measured NV spin contrast and can lead to an enhanced magnetic sensitivity. At present, (111) diamond material has been optimized

for nanoscale magnetic sensing and imaging applications. In this work, we seek to achieve thick (111) NV ensembles suitable for bulk precision magnetometry applications.

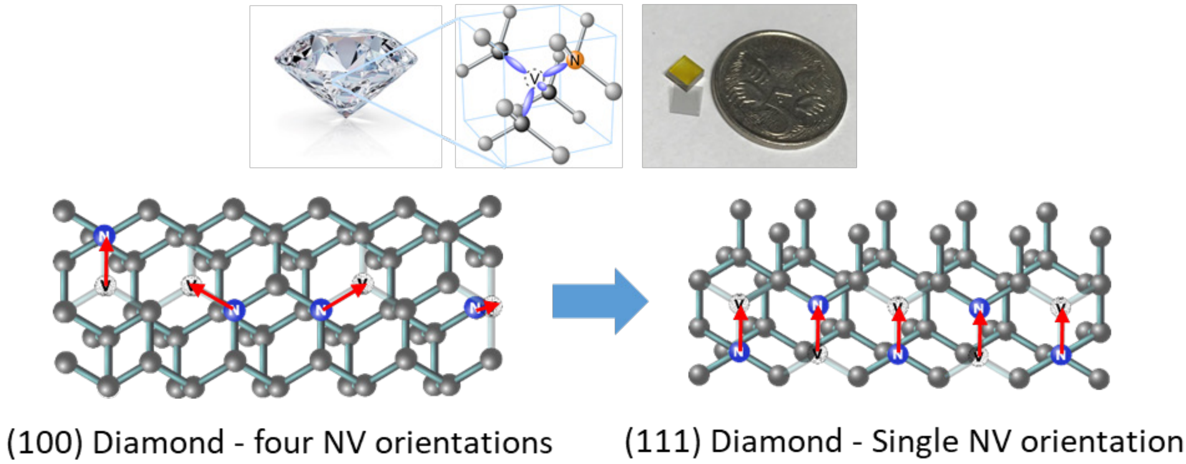

Figure 1: Engineering NV centres in diamond. Left, NV centres grown in four distinct orientations on (100) diamond substrates. Right, aligned NV centres grown on (111) substrates.

Using the commercial-grade diamond CVD reactor at the University of Melbourne, the team has engineered the first ultrapure (111) diamond layers in Australia. This represents the starting point for the NV incorporation study. We have characterized the surface morphology, optical properties and the growth rates from a series of nine diamond samples. The team has also refined the surface treatment prior to CVD growth to reduce substrate imperfections seeding into the grown layers. Figure 2 illustrates the results from the latest series of (111) diamond growths, note the shapes in the corners of the diamond are regions where the diamond was protected in order to determine the growth rate from each sample.

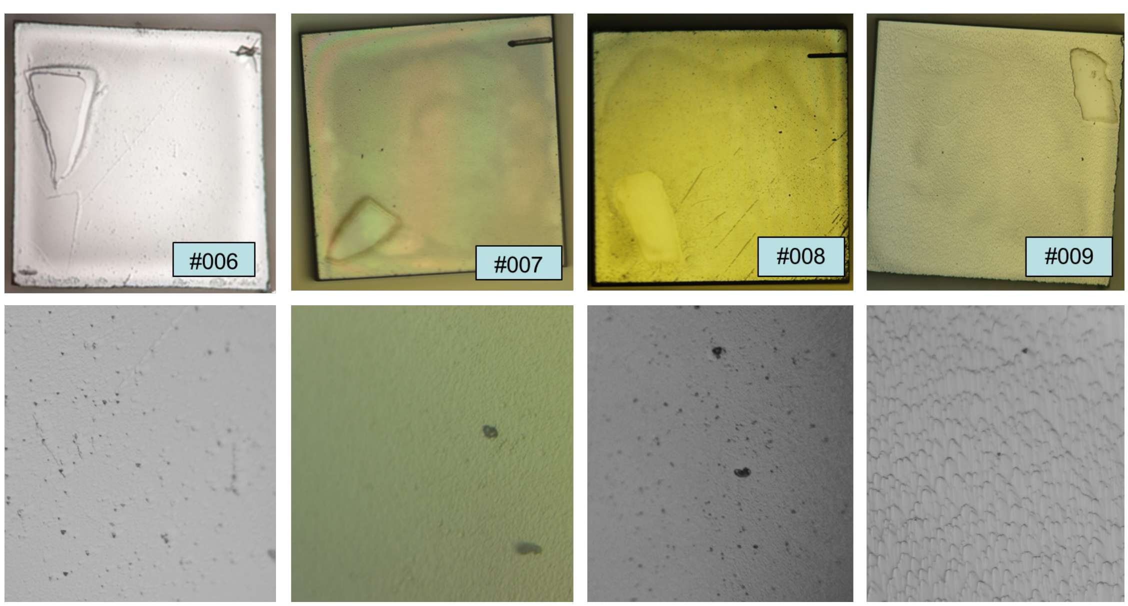

Figure 2: Series of ultrapure diamond growths with various growth parameters. Note: regions of the diamonds were covered to enable the growth rates to be determined.

Table 1 presents the growth parameters for each sample and the resulting growth rate. The surface morphology was found to change with the methane/hydrogen ratio, with a CH_4/H ratio of 0.2 for growth 6 appearing optimal in terms of the overall growth rate and surface roughness.

Table 1: Quantum-grade (111) diamond growths.

Sample	**H**	**CH_4**	**Pressure**	**Power**	**Temp.**	**Etch time**	**Growth time**	**Growth thickness**	**Growth rate**
	sccm	sccm	Torr	Watts	°C	hrs	hrs	nm	nm/hr
006	500	1.0	90	3000	800	1	4.58	1,830	400
007	500	1.0	120	4000	900	1	2.5	450	172
008	1000	1.0	120	4000	900	0.17	2.5	133	52
009	1000	1.0	90	3000	800	0.17	2.5	800	311

The initial growths have allowed us to narrow the parameter space for smooth high quality (111) diamond growth. The second phase of the program focused on the characterization platforms to evaluate the magnetic sensitivitity, bandwidth and dynamic range of the grown materials. This was successfully achieved by the project's end. The commissioning of the new diamond CVD reactor will allow the primary material research questions to be addressed with and without isotopic enrichment. Our team hope this will become part of a future funded program of work which leverages what we have achieved and established as part of this current program.

Thank you for your support in helping AFOSR discover, shape and champion basic science research that profoundly impacts that future of the Air and Space Forces!